10-01-04 10813811

P.B.5818 - Patentlaan 2
2280 HV Rijswijk (ZH)
☎ +31 70 340 2040
TX 31651 epo nl
FAX +31 70 340 3016

Europäisches Patentamt | European Patent Office | Office européen des brevets

Generaldirektion 1 | Directorate General 1 | Direction Générale 1

Bird, William Edward
Bird Goen & Co.
Klein Dalenstratt 42A
3020 Winksele
BE

RECEIVED
05 APR. 2004

Datum/Date
29/03/04

Zeichen/Ref./Réf.	Anmeldung Nr./Application No./Demande n°./Patent Nr./Patent No./Brevet n°.
I2323-EP/go/aj	03447073.2 1247
Anmelder/Applicant/Demandeur/Patentinhaber/Proprietor/Titulaire	
INTERUNIVERSITAIR MICROELEKTRONICA CENTRUM VZW	

Übersendung von/Transmission of/Envoi de

Antrag vom/Request dated/Requête du 18/03/04

- ☐ Kopien bei Akteneinsicht nach Regel 94(3) EPÜ
  Copies in the case of inspection of files pursuant to Rule 94(3) EPC
  Copies en cas d'inspection publique selon la règle 94(3) CBE
- ☐ Beglaubigung
  Certification
  Certification
- ☒ 1 Prioritätsbeleg(e)/priority document(s)/document(s) de priorité R. 94(4)
- ☐ ___ Ausfertigung(en) der Patenturkunde nach Regel 54(2) EPÜ
  Duplicate of the patent certificate pursuant to Rule 54(2) EPC
  Duplicata du certificat de brevet, selon la Règle 54(2) CBE
- ☐ Auszug aus dem Register nach Regel 92(3) EPÜ
  Extract from the register pursuant to Rule 92(3) EPC
  Extrait du registre selon la Règle 92(3) CBE
- ☐ Auskunft aus den Akten nach Regel 95 EPÜ
  Communication of information contained in the files pursuant to Rule 95 EPC
  Communication d'informations contenues dans la dossier selon la Règle 95 CBE
- ☐ Akteneinsicht nach Regel 94(2) EPÜ
  Inspection of files pursuant to Rule 94(2) EPC
  Inspection publique selon la Règle 94(2) CBE

PERON L (TEL:3632)

10-01-04 10813811

Europäisches Patentamt

European Patent Office

Office européen des brevets

Bescheinigung

Certificate

Attestation

Die angehefteten Unterlagen stimmen mit der ursprünglich eingereichten Fassung der auf dem nächsten Blatt bezeichneten europäischen Patentanmeldung überein.

The attached documents are exact copies of the European patent application described on the following page, as originally filed.

Les documents fixés à cette attestation sont conformes à la version initialement déposée de la demande de brevet européen spécifiée à la page suivante.

Patentanmeldung Nr. Patent application No. Demande de brevet n°

03447073.2

Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
p.o.

R C van Dijk

Anmeldung Nr:
Application no.: 03447073.2
Demande no:

Anmeldetag:
Date of filing: 31.03.03
Date de dépôt:

Anmelder/Applicant(s)/Demandeur(s):

INTERUNIVERSITAIR MICROELEKTRONICA CENTRUM
VZW
Kapeldreef 75
3001 Leuven
BELGIQUE
VRIJE UNIVERSITEIT BRUSSEL
Pleinlaan 1
1080 Brussel
BELGIQUE

Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
Si aucun titre n'est indiqué se referer à la description.)

Embedded multiple description scalar quantizers for progressive image transmission

In Anspruch genommene Prioriät(en) / Priority(ies) claimed /Priorité(s) revendiquée(s)
Staat/Tag/Aktenzeichen/State/Date/File no./Pays/Date/Numéro de dépôt:

Internationale Patentklassifikation/International Patent Classification/
Classification internationale des brevets:

H03M7/40

Am Anmeldetag benannte Vertragstaaten/Contracting states designated at date of filing/Etats contractants désignées lors du dépôt:

AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IT LU MC NL
PT RO SE SI SK TR LI

EMBEDDED MULTIPLE DESCRIPTION SCALAR QUANTIZERS FOR PROGRESSIVE IMAGE TRANSMISSION

Field of the Invention

The present invention relates to communication of digital signals, more particularly to a method and a device for transmission and/or reception of digital signals using diversity (e.g. Multiple Description Coding – MDC) to overcome channel impairments, as well as to the signals themselves and a network for transmitting and receiving the signals

Technical Background

A new family of communication services involving the delivery of image data over bandwidth limited and error prone channels as packet networks and wireless links has emerged in the last few years. In order to increase the reliability over these types of channels, diversity is commonly resorted to, besides error correction techniques. Multiple Description Coding (MDC) has been introduced to efficiently overcome channel impairments over diversity-based systems allowing decoders to extract meaningful information from a subset of a bit-stream.

In his PhD. Thesis, which can be found in electronic format on http://lcavwww.epfl.ch/~goyal/Thesis/, Vivek K. Goyal offers an overview of MDC in general and achievable rate-distortion regions. The focus of previous research was laid on finding the optimal achievable rate-distortion regions and their boundaries, as described in L. Ozarow, "On a source coding problem with two channels and tree receivers," *Bell Syst. Tech. J.*, vol. 59, pp. 1909-1921, 1980, and in A. A. El Gamal and T. M. Cover, "Achievable rates for multiple descriptions," *IEEE Trans. Inform. Th.*, vol. IT-28, no. 6, pp. 851-857, 1982. This is followed by the design of practical compression systems to meet these theoretical boundaries. Examples include methods based on quantization as described in V. A. Vaishampayan, "Design of multiple description scalar quantizers," *IEEE Trans. Inform. Th.*, vol. 39, no. 3, pp. 821 - 834, 1993, and in V. A. Vaishampayan and J. Domaszewicz, "Design of entropy-constrained multiple description scalar quantizers," *IEEE Trans. Inform. Theory*, vol. 40, no. 1, pp. 245-250, 1994, and methods based on multiple description transform as described in J. Batllo and V. Vaishampayan, "Asymptotic performance of multiple description transform codes," *IEEE Trans. Inform.*

Theory, vol. 43, no. 2, pp. 703-707, 1997, and in V. Goyal, J. Kovacevic, R. Arean, and M. Vetterli, "Multiple description transform coding of images," *Proc. IEEE Int. Conf. Image Proc.* ICIP'98, pp. 674-678, 1998. A design of Multiple Description Scalar Quantizers (MDSQ) is pioneered in V. A. Vaishampayan, "Design of multiple description scalar quantizers," *IEEE Trans. Inform. Th.*, vol. 39, no. 3, pp. 821 - 834, 1993 under an assumption of fixed length codes and fixed codebook sizes. Significant improvements are achieved in V. A. Vaishampayan and J. Domaszewicz, "Design of entropy-constrained multiple description scalar quantizers," *IEEE Trans. Inform. Theory*, vol. 40, no. 1, pp. 245-250, 1994 where the design of the quantizers is subject to the constraint of a given entropy, and not of a given codebook size.

In order to achieve robust communication over unreliable channels the MDC system has to deliver highly error-resilient bit-streams characterised by a corresponding high level of redundancy. Additionally, a fine grain scalability of the bit-stream is a desirable feature for bandwidth varying channels. A system conceived so as to meet these requirements is described in T. Guionnet, C. Guillemot, and S. Pateux, "Embedded multiple description coding for progressive image transmission over unreliable channels," *Proc. IEEE Int. Conf. Image Proc.*, ICIP 2001, pp. 94 - 97, 2001, where a progressive MDC algorithm is based on Multiple Description Uniform Scalar Quantizers (MDUSQ). Moreover, for a high level of redundancy and for low bit-rates, the approach of this document outperforms the embedded MDC algorithm based on a polyphase transform as proposed in W. Jiang and A. Ortega, "Multiple description coding via polyphase transform and selective quantization," *Proc. SPIE Int. Conf. Visual Comm. Image Proc.*, VCIP'99, San Jose, USA, pp. 998-1008, 1999.

The system proposed in V. A. Vaishampayan, "Design of multiple description scalar quantizers," *IEEE Trans. Inform. Th.*, vol. 39, no. 3, pp. 821 - 834, 1993, relies on the ability to design scalar quantizers with nested thresholds. A source signal or input signal, generally called "a source", represented by a random process $\{X_n,\ n \in \mathbf{Z}_+\}$ with zero mean and variance σ_X^2 is quantized by side quantizers $Q_S^m : R \to \{0,1,\ldots,K\text{-}1\}$, m being a value between 1 and the number of side quantizers available, for example $m = 1, 2$, and K being the number of quantization intervals of a side quantizer for a quantization level. In the example given with two side quantizers, each of the two quantizers outputs an index $q_k^m, k \in \mathbf{Z}_+$ for a quantization level, which indexes can be separately used to estimate the source sample. A reconstruction where $Q_S^m(x) = q_k^m$ must be the centroid of the cell or

quantization interval $Q_S^{m^{-1}}(q_k^m)$. If both indices $Q_S^1(x)=q_k^1$ and $Q_S^2(x)=q_k^2$ are received, the reconstruction is the centroid of the intersection $Q_C^{-1}(q_k^1,q_k^2)= Q_S^{1^{-1}}(q_k^1)\cap Q_S^{2^{-1}}(q_k^2)$ represented by the central inverse quantizer. The number of diagonals covered in the index assignment matrix triggers the redundancy between the two descriptions, as described in V. A. Vaishampayan, "Design of multiple description scalar quantizers," *IEEE Trans. Inform. Th.*, vol. 39, no. 3, pp. 821 - 834, 1993.

Quantization methods based on embedded scalar quantizers are previously proposed in the literature – see for e.g. D. Taubman and M. W. Marcellin, *JPEG2000 - Image Compression: Fundamentals, Standards and Practice.* Hingham, MA: Kluwer Academic Publishers, 2001. In embedded quantization, the partition cells or quantization intervals at higher quantization rates are embedded in the quantization intervals at lower rates. A quantization rate relates to the number of quantization intervals at a quantization level. A set of embedded side quantizers $Q_S^{m,0}$, $Q_S^{m,1}$,..., $Q_S^{m,P}$ with $m=1,2$ the number of side quantizers, and P+1 the number of quantization levels, and a set of embedded central quantizers Q_C^0, Q_C^1, ..., Q_C^P where $Q_C^{p^{-1}}(q_k^1,q_k^2)=Q_S^{1,p^{-1}}(q_k^1)\cap Q_S^{2,p^{-1}}(q_k^2)$ for any quantization level p, $0\le p\le P$ are assumed. The quantization intervals of any quantizer $Q_S^{m,p}$ and Q_C^p are embedded in the quantization intervals of the quantizers $Q_S^{m,P}$, $Q_S^{m,P-1}$,..., $Q_S^{m,p+1}$ and Q_C^P, Q_C^{P-1},..., Q_C^{p+1} respectively. It is considered that the quantizer at level p (e.g. $Q_S^{m,p}$) is finer than the quantizer at level $p+1$ (e. g. $Q_S^{m,p+1}$) if at least one of the quantization intervals of the quantizer at level $p+1$ is split into at least two quantization intervals at level p.

The number of side quantization intervals of the lowest-rate quantizer $Q_S^{m,P}$ is denoted by N and the number of quantization intervals in which an arbitrary side quantization interval $S_k^{m,p}$ of $Q_S^{m,p}$ is divided is denoted by L_k. The maximum number of intervals in which any side quantization interval $S_k^{m,p}$ is partitioned over all quantization levels is denoted by N_p, with $L_k\le N_p$ for any k. Starting from the lowest-rate quantizer $Q_S^{m,P}$, each side quantization interval $S_{k_P}^{m,P}$, $0\le k_P<N$ is divided into a number of L_{k_P} quantization intervals $S_{k_P,k_{P-1}}^{m,P-1}$, $0\le k_{P-1}<L_{k_P}$ of $Q_S^{m,P-1}$. In general, for each side-quantizer $Q_S^{m,p}$ one associates to any $X\in S_{k_P,k_{P-1},\dots,k_p}^{m,p}$ the quantizer index $k_P,k_{P-1},\dots,k_p$. This allows to obtain the indices of lower rate quantization by leaving aside components of higher rate quantization, similar to the uniform embedded scalar quantizers as described in D. Taubman and M. W. Marcellin, *JPEG2000 - Image Compression: Fundamentals,*

Standards and Practice. Hingham, MA: Kluwer Academic Publishers, 2001.

Summary of the Invention

The present invention aims at providing a method and device for robust progressive image transmission of encoded digital signals over unreliable channels with variable bandwidth which yield a better rate-distortion performance compared to known Multiple Description Uniform Scalar Quantizers (MDUSQ). The signals may correspond to detectable physical quantities, such as, but not limited to, pressures, voltages, magnetic field strengths, photon energies and counts, that capture conditions at a particular time and place. Communication or transmission of those signals allows for sight and sound reproduction.

According to the present invention, a type of embedded scalar quantizers for Multiple Description Coding (MDC) systems are introduced, which shall be referred to as Embedded Multiple Description Scalar Quantizers (EMDSQ) hereinafter. The EMDSQ of the present invention meet features desired for robust progressive image transmission over unreliable channels, such as for example a high redundancy level, fine grain rate adaptation and progressive transmission of each description. For an erasure channel model characterised by burst errors, progressive transmission also provides quality improvement for the central reconstruction due to the use of undamaged data from partially damaged received side channels. The reconstruction of the central channel can be performed if the receiver knows where the burst error occurs. To satisfy this requirement, techniques such as inserting synchronisation markers in the bit-stream can be used.

The EMDSQ of the present invention may be incorporated in any suitable coding system such as a DCT coding or, for example, a wavelet-based coding system that employs a Quad Tree (QT) coding algorithm as described in A. Munteanu, J. Cornelis, G. Van der Auwera, and P. Cristea, "Wavelet-based lossless compression scheme with progressive transmission capability," *Int. J. Imaging Systems and Tech.*, vol. 10, no. 1, pp. 76-85, Jan. 1999.

The present invention provides a method for transmitting a digital signal, the method comprising quantizing a source digital signal to generate with different quantizations at least a first and a second bit-stream, of which at least one bit-stream has been generated by an embedded quantization, transmitting at least one of the at least first

and second bit-streams and generating a dequantized digital signal from at least parts of one of the transmitted at least first and second bit streams, whereby if in the generation of the dequantized digital signal the parts of the at least first and second bit-streams are combined, the combined dequantized signal is generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of the at least first and second bit-streams.

Each quantization level has a quantization rate. A quantization rate corresponds to the number of quantization intervals a digital signal is divided into at a certain quantization level. At least one bit-stream generated by an embedded quantization may be generated by an embedded quantization where at least two quantization intervals at lower quantization rate are split into a different number of quantization intervals at higher quantization rate. At least one bit-stream generated by an embedded quantization may be generated by a non-uniform embedded quantization. At least one bit-stream generated by a non-uniform embedded quantization may be generated by a non-uniform embedded dead zone quantization. At least one bit-stream generated by a non-uniform embedded dead zone quantization is generated by a non-uniform embedded double dead zone quantization.

Alternatively, at least one bit-stream generated by an embedded quantization may be generated by a uniform embedded quantization. At least one bit-stream generated by a uniform embedded quantization may be generated by a uniform embedded dead zone quantization. At least one bit-stream generated by a uniform embedded dead zone quantization may be generated by a uniform embedded double dead zone quantization.

Instead of one or more bit-streams, each bit-stream may be generated by an embedded quantization.

A method according to the present invention may furthermore comprise selecting end points of quantization intervals of a quantizer such that at least one of the end points does not coincide with end points of a quantization interval of another quantizer. The embedded quantization may comprise at least three levels, preferably more than seven levels, and still more preferred more than ten levels. The quantizing of the source digital signal may comprise an embedded successive approximation quantization at every quantization level.

The present invention also provides a device for transmitting a digital signal. The

device comprises a quantizing means for quantizing a source digital signal to generate with different quantizations at least a first and a second bit-stream, of which at least one bit-stream has been generated by an embedded quantization, and transmitting means for transmitting at least one of the at least first and second bit-streams. The quantizing means are such that when a dequantized digital signal is generated from at least parts of one of the transmitted at least first and second bit streams, if in the generation of the dequantized digital signal the parts of the at least first and second bit-streams are combined, the combined dequantized signal is generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of the at least first and second bit-streams.

At least one bit-stream generated by an embedded quantization may be generated by an embedded quantizer where at least two quantization intervals at lower quantization rate are split in a different number of quantization intervals at higher quantization rate. At least one bit-stream generated by an embedded quantizer may be generated by a non-uniform embedded quantizer. At least one bit-stream generated by a non-uniform embedded quantizer may be generated by a non-uniform embedded dead zone quantizer. At least one bit-stream generated by a non-uniform embedded dead zone quantizer may be generated by a non-uniform embedded double dead zone quantizer.

Alternatively, a device according to the present invention may be such that at least one bit-stream generated by an embedded quantizer is generated by a uniform embedded quantizer. At least one bit-stream generated by a uniform embedded quantizer may be generated by a uniform embedded dead zone quantizer. At least one bit-stream generated by a uniform embedded dead zone quantizer may be generated by a uniform embedded double dead zone quantizer.

Each bit-stream may be generated by an embedded quantizer.

The quantizing means may include means for selecting end points of quantization intervals of a quantization such that at least one of the end points does not coincide with end points of a quantization interval of another quantizer.

The embedded quantization may comprise at least three levels, preferably more than seven levels, and still more preferred more than ten levels.

The quantizing means may comprise an embedded successive approximation quantizer for carrying out an embedded successive approximation quantization at every

quantization level.

A device according to the present invention may be located in a node of a telecommunications network.

The present invention also provides a device for receiving a digital signal. The device comprises receiving means for receiving at least a first and a second bit-stream, and dequantizing means for generating a dequantized digital signal from the received first and second bit-streams. The dequantizing means comprise combining means for combining, in the generation of the dequantized digital signal, the at least first and second bit-streams, the combined dequantized signal being generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of the at least first and second bit-streams.

At least one of the first and the second bit-streams may be generated by an embedded quantizer where at least two quantization intervals at lower quantization rate are split in a different number of quantization intervals at higher quantization rate. At least one of the first and second bit-streams generated by an embedded quantizer may be generated by non-uniform embedded quantizer. At least one of the first and second bit-streams generated by a non-uniform embedded quantizer may be generated by a non-uniform embedded dead zone quantizer. At least one of the first and second bit-streams generated by a non-uniform embedded dead zone quantizer may be generated by a non-uniform embedded double dead zone quantizer.

At least one of the first and second bit-streams generated by an embedded quantizer may be generated by a uniform embedded quantizer. At least one of the first and second bit-streams generated by a uniform embedded quantizer may be generated by a uniform embedded dead zone quantizer. At least one of the first and second bit-streams generated by a uniform embedded dead zone quantizer may be generated by a uniform embedded double dead zone quantizer.

Each bit-stream is generated by an embedded quantizer.

The dequantizing means may comprise at least three levels, preferably more than seven levels, and still more preferred more than ten levels.

A device according to the present invention may be located in a node of a telecommunications network.

The present invention also provides two or more signals generated by any of the

methods of described above.

The present invention furthermore provides a telecommunications network comprising a device according to the present invention and as described above. The present invention also includes a software product such as a computer program product, which when executed on a computing device executes any of the methods of the present invention. The present invention also includes this software product stored on a signal medium such as an optical or magnetic disk or a magnetic tape or similar.

These and other characteristics, features and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention. This description is given for the sake of example only, without limiting the scope of the invention. The reference figures quoted below refer to the attached drawings.

Brief Description of the drawings

Fig. 1 illustrates two-channel EMDSQ according to an embodiment of the present invention: the side quantizers are $Q_S^{m,p}$, with the number of side quantizers being $m=1,2$, and there being two quantization levels $p=0,1$. $Q_C^p(x)$ represents the central quantizer. Neglecting the signs, the side and central quantization intervals are of the form $S_{k_0}^{m,1}$, $S_{k_0,k_1}^{m,0}$ and $C_{k_0}^1$, C_{k_0,k_1}^0, respectively.

Fig. 2 illustrates four-channel EMDSQ according to an embodiment of the present invention: the side quantizers are $Q_S^{m,p}$, with the number of side quantizer being $m=1...4$, and there being two quantization levels $p=0,1$. The central quantizer is Q_C^p.

Fig. 3 is an illustration of redundancy ρ versus number of channels for $2 \le M \le 7$ in function of a quantization level p, where the total number of quantization levels is $P=5$, and $0 \le p \le 5$.

Fig. 4 is a four-level representation of a first side quantizer $Q_S^{1,p}$ for two-channel EMDSQ for an example with granular region ranging from 0 to 23.

Fig. 5 illustrates a comparison of side and central rate-distortion performance between EMDSQ and MDUSQ.

Fig. 6 illustrates a comparison of side and central rate-distortion performance obtained on a "Lena" image with a resolution of 512x512 pixels with an MD-QT code employing EMDSQ according to an embodiment of the present invention and MDUSQ

according to the prior art respectively.

Fig. 7 illustrates performance (PSNR) of the central reconstruction of MD-QT coding based on EMDSQ compared to the one based on MDUSQ for bit rates ranging from 0.125 to 4 bpp.

Fig. 8 illustrates a transmission system according to an embodiment of the present invention, with at the transmitter side a plurality of quantizers for generating with different quantizations, from a source digital signal, a plurality of bit-streams, and with at the receiver side a plurality of dequantizers for generating, from at least partially received bit-streams, a plurality of inverse quantized bit-streams which may be combined to obtain a better approximation of the source signal.

Fig. 9 illustrates a transmission system according to another embodiment of the present invention, with at the transmitter side a quantizer for generating with different quantizations, from a source digital signal, a plurality of bit-streams, and with at the receiver side a combined central dequantizer for generating, from at least partially received bit-streams, a combined inverse quantized bit-stream.

Fig. 10 and 11 show implementations of embodiments of the present invention in computers and embedded processors.

Acronyms

EMDSQ: Embedded Multiple Description Scalar Quantizers
MDC: Multiple Description Coding
MDSQ: Multiple Description Scalar Quantizers
MD-QT: Multiple Description-Quad Tree
MDUSQ: Multiple Description Uniform Scalar Quantizers
PDF: probability density function
PSNR: peak signal to noise ratio
SDC: Single-Description Coder

Description of the illustrative embodiments.

The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for

illustrative purposes. Where the term "comprising" is used in the present description and claims, it does not exclude other elements or steps.

Furthermore, any terms such as first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequential or chronological order. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other sequences than described or illustrated herein. μ

The present invention relates to data communication, more particularly to transmission of multiple bit-streams over a channel or over a plurality of channels, whereby each bit-stream in itself can reconstruct an approximation of the original data, for example an approximation of the original image if the source data is image data. Hence, the present invention does not require that all digital streams are used to create the original signal at a receiver. However, for a dispersive or noisy environment, the more bit-streams that are received and combined with each other, the better the reconstructed data, e.g. image is likely to be. Each, or at least a plurality, of the bit-streams are quantized in a different way. The process of the present invention is illustrated in Fig. 8 and in Fig. 9.

At the sender or transmitter side of a transmission system, or at any intermediate part or node of the system where quantization is required, a source digital signal S, such as e.g. a source video signal (an image), or more generally any type of input data to be transmitted, is quantized in a quantizer Q, or in a plurality of quantizers Q_1, Q_2, ..., Q_N, so as to form a number of N bit-streams S_1, S_2, ..., S_N. The source signal can be a function of one or more continuous or discrete variables, and can itself be continuous or descrete-valued. The generation of bits from a continuous-valued source inevitably involves some form of quantization, which is simply an approximation of a quantity with an element chosen from a discrete set. Each of the generated N bit-streams S_1, S_2, ..., S_N may or may not be encoded subsequently, for example, entropy encoded, in encoders C_1, C_2, ..., C_N before transmitting them over a channel ≈. An encoder produces from the source signal a signal which is compatible with the channel. The channel is the physical medium that conducts the transmitted signal. After transmission over the channel the signals are received at a receiver or decoder side. A receiver or decoder attempts to recreate the message from the received signals. The received signals may be distorted or include

deletions (e.g. caused by interference). The at least partially received signals $P_1, P_2, \ldots, P_N$ are inverse quantized or dequantized at the receiver side of the transmission system. The terms "inverse quantizing" and "dequantizing" have the same meaning, and one can be replaced by the other in the present document. The inverse quantization or dequantizing may be done in a separate dequantizer $Q_1^{-1}, Q_2^{-1}, \ldots, Q_N^{-1}$ for each bit-stream or in a single dequantizer for all the streams. Each inverse quantized signal can be used alone for displaying an approximation of the source digital signal, e.g. for displaying an approximation of a source image. Alternatively, at least two inverse quantized signals may be combined into an inverse quantized and combined signal which can be used e.g. for displaying a better approximation of the transmitted image. Alternatively, the inverse quantization or dequantizing may be done in a combined inverse quantizer, also leading to an inverse quantized and combined signal which can be used e.g. for displaying the transmitted image.

For the quantizers of the present invention, EMDSQ, according to an embodiment the side quantizers $Q_S^{m,p}$ are non-uniform embedded quantizers, thus for any $0 \le p \le P$ there exist k, j, $k \ne j$ such that $L_k \ne L_j$. The example depicted in Fig. 1 illustrates an instantiation of a two-channel EMDSQ according to the present invention. In view of simplification, only two quantization levels $p = 0,1$ are considered. It is noticed for instance that the quantization intervals $s_{-,1}^{2,1}$ and $s_{+,1}^{2,1}$ of the second-channel embedded quantizer $Q_S^{2,1}$ are divided respectively into three quantization intervals $s_{\pm,1,0}^{2,0}$, $s_{\pm,1,1}^{2,0}$ and $s_{\pm,1,2}^{2,0}$ of the higher rate quantizer $Q_S^{2,0}$. On the contrary, the dead zone $s_0^{2,1}$ of the second-channel embedded quantizer $Q_S^{2,1}$ is not divided and is transformed into $s_{0,0}^{2,0}$ of $Q_S^{2,0}$.

A uniform entropy-coded scalar quantizer is optimal for high rates, and nearly optimal for lower rates, as described in D. Taubman and M. W. Marcellin, *JPEG2000 - Image Compression: Fundamentals, Standards and Practice*, Hingham, MA: Kluwer Academic Publishers, 2001. Furthermore, the above book also describes that, for input data with symmetric probability density function (PDF), the rate-distortion behaviour at low rates can be improved by widening the quantization interval located around zero, that is, by using deadzone uniform scalar quantizers. The rate-distortion function gives the minimum rate needed to approximate a source signal up to a given distortion. It can be noticed that the central quantizer Q_C^1 and Q_C^0 obtained from the side quantizers $Q_S^{1,1}$, $Q_S^{2,1}$ and $Q_S^{1,0}$, $Q_S^{2,0}$ presented in Fig. 1 is a double-deadzone embedded quantizer, i.e. a

quantizer having equal quantization intervals with a size or width Δ, except for the quantization interval around zero which has a size or width 2Δ. Hence, it shows the above-mentioned characteristics of improved rate-distortion behaviour.

For two-channel EMDSQ, an analytical expression of an embodiment of a proposed embedded side-quantizer for the first channel is:

$$Q_S^{1,p}(x) = \begin{cases} 0 & x \in [-A_{Inf}^{1,p}, A_{Inf}^{1,p}) \\ Q_A^{1,p}(x) & x \in \left[-A_{Sup}^{1,p}, -A_{Inf}^{1,p}\right) \cup \left[A_{Inf}^{1,p}, A_{Sup}^{1,p}\right) \\ Q_B^{1,p}(x) & x \in \left[-B_{Sup}^{1,p}, -B_{Inf}^{1,p}\right) \cup \left[B_{Inf}^{1,p}, B_{Sup}^{1,p}\right) \end{cases} \qquad \text{Eq. (1)}$$

where:

$$Q_A^{1,p}(x) = sign(x)\left(\left\lfloor \frac{|x|}{2^p\Delta} + \frac{\xi}{2^p} \right\rfloor - (k + p\%2)\right) \qquad \text{Eq. (2)}$$

$$Q_B^{1,p}(x) = sign(x)\left(\left\lfloor \frac{|x|}{2\cdot 2^p\Delta} + \frac{\xi}{2\cdot 2^p} + \frac{k + (1 - p\%2)}{2} \right\rfloor\right) \qquad \text{Eq. (3)}$$

The boundary points in Eq. (1) are defined as follows:

$A_{Sup}^{1,p} = \Delta(2^p(3k+1+2p\%2)-\xi)$, $A_{Inf}^{1,p} = \Delta(2^p(3k+2p\%2)-\xi)$,

$B_{Sup}^{1,p} = \Delta(2^p(3k+3-p\%2)-\xi)$, $B_{Inf}^{1,p} = \Delta(2^p(3k+1-p\%2)-\xi)$.

In the above equations and formulae:

$\lfloor a \rfloor$ denotes the integer part of a,

$\Delta > 0$ is the size or width of a quantization interval for Q_C^0,

$p\%2 = p - 2\cdot\lfloor p/2 \rfloor$, and

ξ (with $\xi < 1$) determines the size or width of the deadzone.

[a, b) denotes an interval which is closed in a but open in b, that is if $x \in [a, b)$ then $a \le x < b$

The index $k \in Z_+$ determines the size or width of the quantizer granular region, which is the interval [y_k-Δ/2, y_k-Δ/2]; source samples in this interval will be approximated within ± Δ/2 by their quantized values.

Since the parameter ξ controls the size or width of the central deadzone, the central deadzone being one of the quantizer intervals by definition, by tuning its value, corresponding families of embedded quantizers may be obtained. It should be noted that, when $\xi = 1/2$, the central quantizer is uniform, while when $\xi = 0$, the deadzone width is 2Δ; this is the case exemplified in Fig. 1. Negative values of the parameter ξ are further widening the deadzone, as described in the JPEG2000 book mentioned above.

Generalisation of the invention to M channels EMDSQ

M channel quantizers can only be formulated analytically, since it is not possible to graphically build an M-dimensional matrix to apply Vaishampayan's method.

Taking as a starting point equation Eq. (1) that describes an embodiment of the first channel quantizer corresponding to the two-channel EMDSQ, it is possible to generalise the analytical formula so as to obtain an embodiment for M-channels, as shown below:

$$Q_S^{m,p}(x)=\begin{cases} Q_A^{m,p}(x) & x\in\left[-A_{Sup}^{m,p},-A_{Inf}^{m,p}\right)\cup\left[A_{Inf}^{m,p},A_{Sup}^{m,p}\right) \\ Q_B^{m,p}(x) & x\in\left[-B_{Sup}^{m,p},-B_{Inf}^{m,p}\right)\cup\left[B_{Inf}^{m,p},B_{Sup}^{m,p}\right) \end{cases} \qquad \text{Eq. (4)}$$

with:

$$Q_A^{m,p}(x)=sign(x)\left\lfloor \frac{|x|}{mM^p\Delta}-\frac{M+1-2m}{m}(k+p\%2)\right\rfloor$$
$$Q_B^{m,p}(x)=sign(x)\left\lfloor \frac{|x|}{(M+1-m)M^p\Delta}+\frac{M+1-2m}{M+1-m}(k+1-p\%2)\right\rfloor \qquad \text{Eq. (5)}$$

and the boundary points are defined as follows:

$A_{Sup}^{m,p}=\Delta\cdot M^p((M+1)k+m+(M+1-m)(p\%2))$,

$A_{Inf}^{m,p}=\Delta\cdot M^p((M+1)k+(M+1-m)(p\%2))$,

$B_{Sup}^{m,p}=\Delta\cdot M^p((M+1)k+M+1-m(p\%2))$,

$B_{Inf}^{m,p}=\Delta\cdot M^p((M+1)k+m-m(p\%2))$,

where m, $1\le m\le M$ denotes the channel index.

It is to be noted that the particular example of Eq. (1) is derived from Eq. (4) for $M=2$, $m=1$ and $\xi=0$.

Based on the expressions for $A_{Sup}^{m,p}$, $B_{Sup}^{m,p}$, $A_{Inf}^{m,p}$, $B_{Inf}^{m,p}$ given above, one notices that the size or width $\Delta^{(p)}$ of a quantization interval for the side quantizer $Q_S^{m,p}$ at level p and index m depends on the number of channels M by $\Delta^{(p)}=M^p\Delta^{(0)}$, where $\Delta^{(0)}$ is the size or width of the quantization interval for the highest-rate side quantizer $Q_S^{m,0}$, and $\Delta^{(0)}=m\Delta$ or $\Delta^{(0)}=(M+1-m)\Delta$.

Fig. 2 depicts the case of four channels ($M=4$) and two quantization levels ($0\le p\le 1$). It is to be noted that the quantization intervals of the side quantizers $Q_S^{m,0}$, $1\le m\le 4$ are embedded respectively in the quantization intervals of the side quantizers $Q_S^{m,1}$. It is also to be noted that the central quantizer Q_C^p is a double deadzone embedded quantizer

with quantization interval size or width $\Delta_C^{(p)} = 4^p \Delta_C^{(0)}$, where $\Delta_C^{(0)} = \Delta$ is the quantization interval size or width of Q_C^0. The negative side of the quantizers is not illustrated, but is a mirrored version of the positive side which is shown.

Dependency between redundancy and the number of channels

All approaches that imply MDC involve creating redundancy in the bit-stream transmitted over several channels. By $R_m, 1 \le m \le M$ the rates are denoted, and by $D_m(R_m)$ the corresponding side average distortions over M channels. The average distortion of the central quantizer shall be D_0. The standard source coder, i.e. the single-description coder (SDC), a coder that implies one source coder and one decoder contrary to MDC which implies multiple source encoders and multiple source decoders, minimises D_0 for a given rate R_0. Intuitively, the redundancy is the bit-rate sacrificed compared to the SDC coder in order to lower the D_m distortion. A redundancy function is considered:

$$\rho = \sum_{m=1}^{M} R_m - R_0 \qquad \text{Eq. (6)}$$

where R_0 is the lowest rate needed by any SDC in order to achieve the central D_0 distortion of the MDC. For a fixed D_0, the redundancy ranges from $(M-1)R_0$ (the bit-stream is replicated over the M channels) to 0 (the data is totally uncorrelated over the M channels).

For the lowest-rate case (see example of Fig. 2), the number of central quantizer quantization intervals is $2(M+1)-1$. Hence, the central quantization rate is $R_0 = \log_2(2(M+1)-1)$. Since the number of quantization intervals for all lowest-rate EMDSQ side-quantizers is three, their individual rate is $R_m = \log_2 3$. Thus, formula Eq. (6) for the lowest rate quantizers can be written $\rho_P = M \log_2 3 - \log_2(2M+1)$. Similarly, for level $p = P-1$, the number of quantization intervals of the side quantizers $Q_S^{m,P-1}$ is $4M-1$, which yields a rate of $R_m = \log_2(4M-1)$. The central quantization rate will be $R_0 = (\log_2 2M(M+1)-1)$. Following the same reasoning, for quantization level p, $R_m = \log_2(4M^{P-p}-1)$ and $R_0 = \log_2(2M^{P-p}(M+1)-1)$ are obtained. Consequently, the redundancy for quantization level p can be expressed as follows:

$$\rho_p = M \log_2(4M^{P-p}-1) - \log_2(2M^{P-p}(M+1)-1) \qquad \text{Eq. (7)}$$

From Eq. (7), one can deduce the analytical expression of the normalised redundancy:

$$\rho_p' = \frac{M \log_2(4M^{P-p}-1)}{\log_2(2M^{P-p}(M+1)-1)} - 1 \qquad \text{Eq. (8)}$$

One can conclude that for the EMDSQ the redundancy is directly dependent on the number of channels. Whereas, in the case of two channels, one can trigger the redundancy level by the number of diagonals filled in the index assignment matrix as described in V. A. Vaishampayan, "Design of multiple description scalar quantizers," *IEEE Trans. Inform. Th.*, vol. 39, no. 3, pp. 821 - 834, 1993.

A graphic representation of the redundancy versus the number of channels, given by Eq. (8), is shown in Fig. 3. The theoretical boundary of the redundancy $(M-1)R_0$ is reached when the stream is replicated over M channels and is represented by the upper curve in the graph. It is noticeable that the redundancy between the channels monotonically decreases as the quantization level p increases.

Coding scheme

The use of the EMDSQ according to the present invention into a wavelet-based coding scheme is illustrated, for the particular case of the number of channels being $M=2$. A proposed MD-QT coding system encodes the quantizers' output by using a customised version of the wavelet-based QT coding of the significance maps algorithm described in A. Munteanu, J. Cornelis, G. Van der Auwera, and P. Cristea, "Wavelet-based lossless compression scheme with progressive transmission capability," *Int. J. Imaging Systems and Tech.*, vol. 10, no. 1, pp. 76-85, Jan. 1999. This is only one example of one particular coding algorithm that can used EMDSQ. Any type of coding algorithm, and any type of input source such as for example special domain, wavelet transform or DCT transform, can be used.

Significance map coding

By T^p is denoted the significance threshold from a coding step corresponding to the quantization level p, $0 \le p \le P$; the significance of wavelet coefficients being recorded in a significance map with respect to the applied threshold T^p. By $\mathbf{k}=(k_1,k_2)$ the spatial location of the wavelet coefficient from the wavelet transform matrix is denoted, where k_1 and k_2 stand for the row and column index, respectively. By $Q(\mathbf{k},\mathbf{v})$ a quadrant with top-left co-ordinates $\mathbf{k}=(k_1,k_2)$ and size or width $\mathbf{v}=(v_1,v_2)$ is denoted, where v_1 and v_2 represent the quadrant width and height respectively. In view of simplification identical power-of-

two quadrant dimensions v_1 and v_2 are assumed, i.e. $v_1 = v_2 = 2^J$ for some J. The corresponding quadrant delimiting binary elements in the significance map p is denoted by $Q_b^p(\mathbf{k},\mathbf{v})$. The wavelet image $\mathbf{w} = Q(\mathbf{0},\mathbf{V})$ is a matrix of $V_1 \times V_2$ elements, with $\mathbf{0} = (0,0)$, $\mathbf{V} = (V_1, V_2)$. For any wavelet coefficient, its absolute value and sign are denoted as $w(\mathbf{l})$ and $s(\mathbf{l})$ respectively, where $\mathbf{l} = (l_1, l_2)$ with $0 \le l_1 \le V_1$ and $0 \le l_2 \le V_2$.

The significance of the wavelet coefficients from any $Q(\mathbf{k},\mathbf{v}) \in \mathbf{W}$, $\mathbf{v} \neq (1,1)$ with respect to the applied threshold T^p is recorded in $Q_b^p(\mathbf{k},\mathbf{v})$ and is determined via the operator σ^p:

$$\sigma^p(Q(\mathbf{k},\mathbf{v}))\Big|_{\mathbf{v}\neq(1,1)} = \begin{cases} 1 & \text{if } \exists w(\mathbf{l}) \in Q(\mathbf{k},\mathbf{v}),\ w(\mathbf{l}) \ge T^p \\ 0 & \text{if } \forall w(\mathbf{l}) \in Q(\mathbf{k},\mathbf{v}),\ w(\mathbf{l}) < T^p \end{cases} \qquad \text{Eq. (9)}$$

It is to be noted that the significance operator σ^p determines the significance of a quadrant but not the significance of a coefficient. For an individual wavelet coefficient the significant operator σ^p is no longer applied, and instead, the quantizer index allocation operator, denoted by $\delta(w(\mathbf{l}))$, is utilised.

The EMDSQ by their structure present the particularity that different quantization intervals at quantization level p are divided into different numbers of quantization intervals at the quantization level $p-1$ as shown hereinabove. Thus, it can be deduced that in order to perform the index allocation, the wavelet coefficients have to be compared against the values of the boundary points of quantization intervals at a certain quantization level p. It is considered that an arbitrary quantization interval at level p will be divided into N quantization intervals at level $p-1$. The index allocation operator δ determines the codeword associated to each quantized coefficient as follows:

$$\delta(w(\mathbf{l})) = \begin{cases} S_N & \text{if } T_{\delta,N-1} \le w(\mathbf{l}) < T_{\delta,N} \\ \dots & \\ S_2 & \text{if } T_{\delta,1} \le w(\mathbf{l}) < T_{\delta,2} \\ S_1 & \text{if } T_{\delta,0} \le w(\mathbf{l}) < T_{\delta,1} \end{cases} \qquad \text{Eq. (10)}$$

where the boundary points are denoted as $T_{\delta,n}$, with $0 \le n \le N$ and $T_{\delta,0} < T_{\delta,1} < \dots < T_{\delta,N}$. The manner in which the threshold T^p and boundary points $T_{\delta,n}$ are computed will be described below.

For the first quadtree-partitioning pass, as described in A. Munteanu, J. Cornelis, G. Van der Auwera, and P. Cristea, "Wavelet-based lossless compression scheme with progressive transmission capability," *Int. J. Imaging Systems and Tech.*, vol. 10, no. 1, pp. 76-85, Jan. 1999, the significance of the wavelet image $\mathbf{w}$ is tested with respect to the

threshold T^p. If $\sigma^p(\mathbf{w})=1$, the significance map $Q_b^p(0,\mathbf{v})$ of the wavelet image $\mathbf{w}$ is split into four quadrants $Q_b^p(\mathbf{k}_i,\mathbf{v}/2)$, $1\le i\le 4$, each having half the original parent size or width, with $\mathbf{k}_i$ indicating the origin of each quadrant. The descendent significant quadrants are then further spliced until the leaf nodes (i.e. wavelet coefficients) are isolated. For the leaf nodes, the symbols S_n $(0<n\le N)$ are allocated by applying the index allocation operator $\delta(w(\mathbf{l}))$. Thus, the significance pass records the positions $\mathbf{l}$ of all the leaf nodes newly identified as significant, using a recursive tree structure of quadrants (or a quad-tree structure).

Once the positions and the corresponding symbols of the significant leaf nodes are encoded during the significance pass, p is set to $P-1$. Next, the significance pass is restarted to update the entire quad-tree structure by identifying the new significant leaf nodes. During this stage, only the significance of the previously non-significant nodes and quadrants, i.e. those for which $\delta(w(\mathbf{l}))=S_1$ and $\sigma^{p+1}(Q(\mathbf{k},\mathbf{v}))=0$ respectively, is encoded, and the significant ones are ignored since the decoder has already received this information. Subsequently, the corresponding refinement pass is activated for the significant leaf nodes. The refinement pass is performed with respect to the corresponding refinement threshold $T_r^{p,m}$. The described procedure is repeated, until the complete wavelet image is encoded, i.e. $p=0$, or until the target bit-rate is met.

Coding algorithm

The manner in which the significance thresholds, refinement thresholds and boundary points are computed, is illustrated, for the particular case of the number of channels being $M=2$.

As explained before, the coding passes performed by the proposed MD-QT coding system are the significance pass, employing the significance thresholds $T^{p,m}$, $0\le p\le P$, followed by the refinement pass, utilising the refinement thresholds $T_r^{p,m}$, with m, $1\le m\le 2$ denoting the channel index for the case with two channels.

For the lowest quantization rate P, the starting thresholds corresponding to each channel are $T^{P,1}=2T$ and $T^{P,2}=T$ respectively. Since it is not desirable that the quantizer is characterised by an overload region, or an unbounded interval, the T value is related to the highest absolute magnitude w_{max} of the wavelet coefficients as:

$$T=2^{\lfloor \log_2(w_{max}/3)\rfloor+1} \qquad \text{Eq. (11)}$$

Hence, the maximum number of quantization levels is $P=\lfloor \log_2(w_{max}/3) \rfloor+1$. In general, excepting the lowest quantization rate P, the significance thresholds used for each channel m, $1 \le m \le 2$ are given by:

$$T^{P-x,m} = \frac{T_m}{4^{\lfloor (x+1+(m+1)\%2)/2 \rfloor}} 3^{((x+m-1)\%2)} \qquad \text{Eq. (12)}$$

with $P-x=p$, and $x \ge 1$. The values T_m are of the form $T_1=2T$ and $T_2=4T$ respectively.

Fig. 4 depicts the first channel EMDSQ with granular region ranging from 0 to 24 ($x \in [0,24)$). The significance map coding is performed with respect to the set of thresholds $T^{p,1}$ with the rate of decay given by Eq. (12). For the two-channel EMDSQ case, except for the highest quantization rate P, the description of the quantizers reveals that half of the quantization intervals at level p are divided into three quantization intervals at level $p-1$, while the other half are not divided. Thus, three index allocation operators are considered. In the case $p=P$, the index allocation operator $\alpha(w(\mathbf{l}))$ is used to assign for the leaf-nodes in the quadtree the symbols $s_{\alpha,1}$ and $s_{\alpha,2}$ as follows:

$$\alpha(w(\mathbf{l})) = \begin{cases} s_{\alpha,2} & T_{\alpha,1}^{P,m} \le w(\mathbf{l}) < T_{\alpha,2}^{P,m} \\ s_{\alpha,1} & 0 \le w(\mathbf{l}) < T_{\alpha,1}^{P,m} \end{cases} \qquad \text{Eq. (13)}$$

where $T_{\alpha,1}^{P,m} = T^{P,m}$ and $T_{\alpha,2}^{P,m} = 3T$.

In the case $p<P$ two operators $\beta(w(\mathbf{l}))$ and $\gamma(w(\mathbf{l}))$ are considered, one for each of the two quantization interval types. For the quantization intervals that are divided in three, the index allocation operator $\beta(w(\mathbf{l}))$ is expressed as:

$$\beta(w(\mathbf{l})) = \begin{cases} s_{\beta,3} & T_{\beta,2}^{p,m} \le w(\mathbf{l}) < T_{\beta,3}^{p,m} \\ s_{\beta,2} & T_{\beta,1}^{p,m} \le w(\mathbf{l}) < T_{\beta,2}^{p,m} \\ s_{\beta,1} & T_{\beta,0}^{p,m} \le w(\mathbf{l}) < T_{\beta,1}^{p,m} \end{cases} \qquad \text{Eq. (14)}$$

where the relations between the corresponding quantization interval boundary points are $T_{\beta,1}^{p,m} = T_{\beta,0}^{p,m} + \Delta_C^{(p)}$, $T_{\beta,2}^{p,m} = T_{\beta,0}^{p,m} + 3 \cdot \Delta_C^{(p)}$ and $T_{\beta,3}^{p,m} = T_{\beta,0}^{p,m} + 4 \cdot \Delta_C^{(p)}$, where $T_{\beta,0}^{P-x,m} = ((x+m)\%2)2\Delta_C^{(P-x)}$, $x \ge 1$.

Apart from this, for the remaining half of the quantization intervals that are not divided only one symbol $s_{\gamma,1}$ is assigned through the index allocation operator $\gamma(w(\mathbf{l}))$ as follows:

$$\gamma(w(\mathbf{l})) = s_{\gamma,1} \text{ for } T_{\gamma,0}^{p,m} \le w(\mathbf{l}) < T_{\gamma,1}^{p,m} \qquad \text{Eq. (15)}$$

The relation between the corresponding quantization interval boundary points is $T_{\gamma,1}^{p,m} = T_{\gamma,0}^{p,m} + 2\Delta_C^{(p)}$, where $T_{\gamma,0}^{P-x,m} = ((x+m+1)\%2)4\Delta_C^{(P-x)}$

The purpose of the refinement pass is to perform the index allocation for

coefficients that have already been coded as significant at the previous significance passes. The index allocation is performed with respect to the new updated values of the boundary points. In order to apply the index allocation, the coefficient that must be refined has to be rescaled with respect to the refinement pass threshold $T_r^{p,m}$ given by:

$$T_r^{p,m} = \max(T_{\gamma,1}^{p,m}, T_{\beta,3}^{p,m}) .$$

In order to improve the compression results, the output of the MD-QT coder (significance symbols, quantizer index symbols, signs symbols) may further be entropy coded with an adaptive arithmetic coder, as described in I. H. Witten, R. M. Neal, and J. G. Cleary, "Arithmetic coding for data compression," Communications of the ACM, vol. 30, no. 5, pp. 520-540, June 1987, that uses four different probability models. One model is used to encode the quadrant significance symbols. Another model is used for the sign symbol encoding. Finally, another two models are utilised to entropy code the symbols generated by the index allocation operators $\alpha(w(l))$ and $\beta(w(l))$ respectively. Since the MD-QT output for the quantization intervals that are not divided is represented by only one symbol $s_{\gamma,1}$, it is completely redundant to further encode these symbols.

EXPERIMENTAL RESULTS

To perform a comparison between the EMDSQ according to the present invention and MDUSQ as described in Guionnet et al., both quantizers are applied on a memoryless Laplacian source of a 256x256 matrix of Laplacian random generated numbers with zero mean and $\sigma = 14.6$, simulating a wavelet subband. Fig. 5 shows that comparable results are obtained for the side channel(s) and that the EMDSQ of the present invention outperforms MDUSQ for the central channel. Similar experimental results were obtained varying the standard deviation within the range $12 < \sigma < 90$.

Similar to EMDSQ, the MDUSQ has been integrated in the MD-QT coding scheme, resulting into a common entropy-coding module for both types of quantizers. The results shown in Fig. 6 obtained on the Lena image reveal that on the central channel the EMDSQ outperforms MDUSQ with 0.52-1.08 dB. Similarly, the results obtained on a common image data set given in the Table of Fig. 7 show that in comparison to the prior art MDUSQ, the EMDSQ of the present invention provides constantly better rate-distortion performances on the central channel for all the rates.

Fig. 10 shows the implementation of a coder/decoder which can be used with the present invention implemented using a microprocessor 230 such as a Pentium IV from

Intel Corp. USA, e.g. in a Personal Computer. The microprocessor 230 may have an optional element such as a co-processor 224, e.g. for arithmetic operations or microprocessor 230-224 may be a bit-sliced processor. A RAM memory 222 may be provided, e.g. DRAM. Various I/O (input/output) interfaces 225, 226, 227 may be provided, e.g. UART, USB, I^2C bus interface as well as an I/O selector 228. These may serve to receive a source digital signal. FIFO buffers 232 may be used to decouple the processor 230 from data transfer through these interfaces. A keyboard and mouse interface 234 will usually be provided as well as a visual display unit interface 236. Access to an external memory such as a disk drive may be provided via an external bus interface 238 with address, data and control busses. The various blocks of the circuit are linked by suitable busses 231. The interface to the channel is provided by block 242 which can handle the encoded signals as well as transmitting to and receiving from the channel. Encoded data received by block 242 is passed to the processor 230 for processing.

Alternatively, the circuit of Fig. 10 may be constructed as a VLSI chip around an embedded microprocessor 230 such as an ARM7TDMI core designed by ARM Ltd., UK which may be synthesized onto a single chip with the other components shown. A zero wait state SRAM memory 222 may be provided on-chip as well as an optional cache memory 224. Various I/O (input/output) interfaces 225, 226, 227 may be provided, e.g. UART, USB, I^2C bus interface as well as an I/O selector 228. FIFO buffers 232 may be used to decouple the processor 230 from data transfer through these interfaces. A counter/timer block 234 may be provided as well as an interrupt controller 236. Access to an external memory may be provided an external bus interface 238 with address, data and control busses. The various blocks of the circuit are linked by suitable busses 231. The interface to the channel is provided by block 242 which can handle the encoded signals as well as transmitting to and receiving from the channel. Encoded data received by block 242 is passed to the processor 230 for processing.

Software programs may be stored in an internal ROM (read only memory) 246. Software programs for carrying out coding and/or encoding, especially the quantising and dequantising in accordance with any of the methods of the present invention may also be stored on the system in executable form. In particular software programs may be provided for quantising and dequantising according to embodiments of the present invention described above to be applied to blocks of data to generate two or more streams of

encoded data. That is the software, for executing on the processor 230 has code for carrying out the function of quantizing a source digital signal to generate with different quantizations at least a first and a second bit-stream, of which at least one bit-stream has been generated by an embedded quantization, transmitting at least one of the at least first and second bit-streams and generating a dequantized digital signal from at least parts of one of the transmitted at least first and second bit streams, whereby if in the generation of the dequantized digital signal the parts of the at least first and second bit-streams are combined, the combined dequantized signal is generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of the at least first and second bit-streams.

Code may be provided so that each quantization level has a quantization rate and at least one bit-stream generated by an embedded quantization is generated by an embedded quantization where at least two quantization intervals at lower quantization rate are split into a different number of quantization intervals at a higher quantization rate. Code may also be provided so that at least one bit-stream generated by an embedded quantization is generated by a non-uniform embedded quantization. Code may also be provided so that at least one bit-stream generated by a non-uniform embedded quantization is generated by a non-uniform embedded dead zone quantization. Code may be provided so that at least one bit-stream generated by a non-uniform embedded dead zone quantization is generated by a non-uniform embedded double dead zone quantization. NCode may be provided so that at least one bit-stream generated by an embedded quantization is generated by a uniform embedded quantization. Code may be provided so that at least one bit-stream generated by a uniform embedded quantization is generated by a uniform embedded dead zone quantization. Code may also be provided so that at least one bit-stream generated by a uniform embedded dead zone quantization is generated by a uniform embedded double dead zone quantization. each bit-stream is generated by an embedded quantization.

The methods described above may be written as computer programs in a suitable computer language such as C and then compiled for the specific processor in the design. For example, for the embedded ARM core VLSI described above the software may be written in C and then compiled using the ARM C compiler and the ARM assembler. Reference is made to "ARM System-on-chip", S. Furber, Addison-Wiley, 2000. The present invention also includes a data carrier on which is stored executable code

segments, which when executed on a processor such as 230 will execute any of the methods of the present invention, in particular will execute quantising and/or dequantising according to embodiments of the present invention described above to be applied to images. The data carrier may be any suitable data carrier such as diskettes ("floopy disks"), optical storage media such as CD-ROMs, DVD ROM's, tape drives, hard drives, etc. which are computer readable.

Fig. 11 shows the implementation of a coder/decoder which can be used with the present invention implemented using an dedicated quantiser/dequantiser module. Reference numbers in Fig. 11 which are the same as the reference numbers in Fig. 10 refer to the same components – both in the microprocessor and the embedded core embodiments.

Only the major differences in Fig. 11 will be described with respect to Fig. 10. Instead of the microprocessor 230 carrying out methods according to the present invention this work is now taken over by a quantiser/dequantiser module 240. Module 240 may be constructed as an accelerator card for insertion in a personal computer. The module 240 has means for carrying out signal coding and/or decoding according to embodiments of the present invention described above. These coders and encoders may be implemented as a separate module 241, e.g. an ASIC (Application Specific Integrated Circuit) or an FPGA (Field Programmable Gate Array) having means for quantising and/or dequnatising according to embodiments of the present invention.

Similarly, if an embedded core is used such as an ARM processor core or an FPGA, a module 240 may be used which may be constructed as a separate module in a multi-chip module (MCM), for example or combined with the other elements of the circuit on a VLSI. The module 240 has means for carrying out quantising and/or dequantising according to embodiments of the present invention. As above, these qunatisers/dequantisers may be implemented as a separate module 241, e.g. an ASIC (Application Specific Integrated Circuit) or an FPGA (Field Programmable Gate Array) having means for quantising and/or dequantising according to embodiments of the present invention described above.

While the invention has been shown and described with reference to preferred embodiments, it will be understood by those skilled in the art that various changes or modifications in form and detail may be made without departing from the scope and spirit of this invention.

Claims

1.- Method for transmitting a digital signal, the method comprising quantizing a source digital signal to generate with different quantizations at least a first and a second bit-stream, of which at least one bit-stream has been generated by an embedded quantization, transmitting at least one of the at least first and second bit-streams and generating a dequantized digital signal from at least parts of one of the transmitted at least first and second bit streams, whereby if in the generation of the dequantized digital signal the parts of the at least first and second bit-streams are combined, the combined dequantized signal is generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of the at least first and second bit-streams.

2.- Method according to claim 1, wherein each quantization level has a quantization rate and at least one bit-stream generated by an embedded quantization is generated by an embedded quantization where at least two quantization intervals at lower quantization rate are split into a different number of quantization intervals at a higher quantization rate.

3.- Method according to claim 2, wherein at least one bit-stream generated by an embedded quantization is generated by a non-uniform embedded quantization.

4.- Method according to claim 3, wherein at least one bit-stream generated by a non-uniform embedded quantization is generated by a non-uniform embedded dead zone quantization.

5.- Method according to claim 4, wherein at least one bit-stream generated by a non-uniform embedded dead zone quantization is generated by a non-uniform embedded double dead zone quantization.

6.- Method according to claim 1, wherein at least one bit-stream generated by an embedded quantization is generated by a uniform embedded quantization.

7.- Method according to claim 6, wherein at least one bit-stream generated by a uniform embedded quantization is generated by a uniform embedded dead zone quantization.

8.- Method according to claim 7, wherein at least one bit-stream generated by a uniform embedded dead zone quantization is generated by a uniform embedded

double dead zone quantization.

9.- Method according to any of the previous claims, wherein each bit-stream is generated by an embedded quantization.

10.- Method according to any of the previous claims, furthermore comprising selecting end points of quantization intervals of a quantizer such that at least one of the end points does not coincide with end points of a quantization interval of another quantizer.

11.- Method according to any of the previous claims, wherein the embedded quantization comprises at least three levels, preferably more than seven levels, and still more preferred more than ten levels.

12.- Method according to any of the previous claims, wherein the quantizing of the source digital signal comprises an embedded successive approximation quantization at every quantization level.

13.- Device for transmitting a digital signal, the device comprising a quantizing means for quantizing a source digital signal to generate with different quantizations at least a first and a second bit-stream, of which at least one bit-stream has been generated by an embedded quantization, and transmitting means for transmitting at least one of the at least first and second bit-streams, the quantizing means being such that when a dequantized digital signal is generated from at least parts of one of the transmitted at least first and second bit streams, if in the generation of the dequantized digital signal the parts of the at least first and second bit-streams are combined, the combined dequantized signal is generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of the at least first and second bit-streams.

14.- Device for receiving a digital signal, the device comprising receiving means for receiving at least a first and a second bit-stream, dequantizing means for generating a dequantized digital signal from the received first and second bit-streams, the dequantizing means comprising combining means for combining, in the generation of the dequantized digital signal, the at least first and second bit-streams, the combined dequantized signal being generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of

the at least first and second bit-streams.

15.- Two or more signals generated by any of the methods of claims 1-12.

16.- A telecommunications network comprising a device according to claim 13 or 14.

Abstract

EMBEDDED MULTIPLE DESCRIPTION SCALAR QUANTIZERS FOR PROGRESSIVE IMAGE TRANSMISSION

The present invention provides a method for transmitting a digital signal. The method comprises quantizing a source digital signal to generate with different quantizations at least a first and a second bit-stream, of which at least one bit-stream is generated by an embedded quantization, transmitting at least one of the at least first and second bit-streams and generating a dequantized digital signal from at least parts of one of the transmitted at least first and second bit streams, whereby if in the generation of the dequantized digital signal the parts of the at least first and second bit-streams are combined, the combined dequantized signal is generated by an embedded dequantizer having at least two quantization levels and having at least one quantization interval at each quantization level which is finer than quantization intervals for dequantizing any of the at least first and second bit-streams.

+ Fig. 2

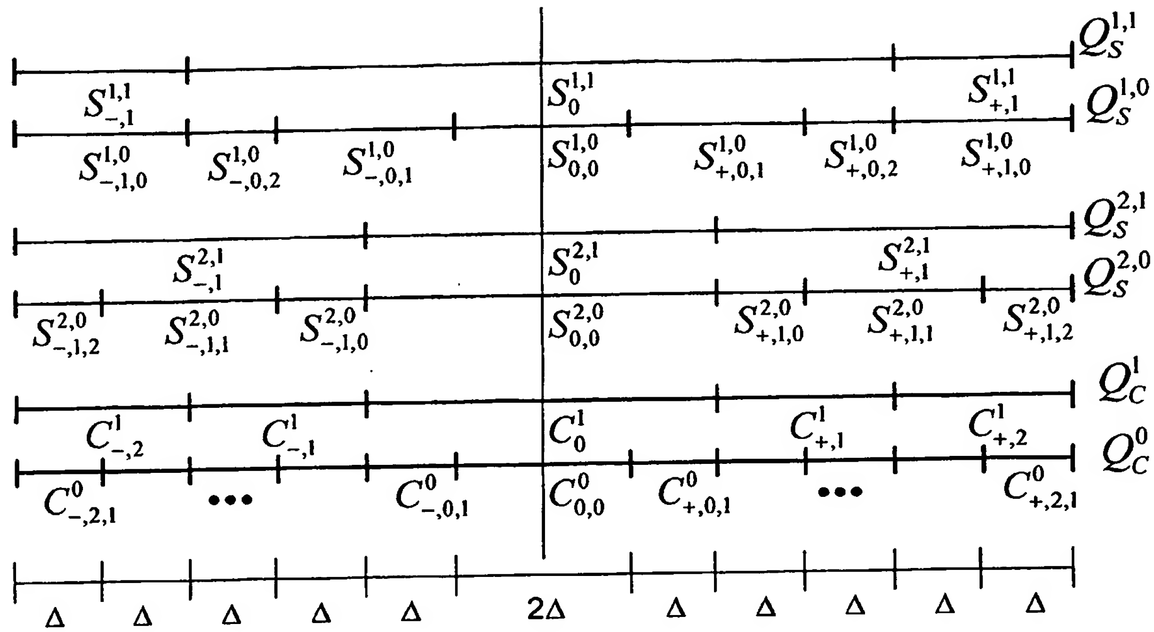

$Q_S^{1,1}$
$Q_S^{1,0}$
$Q_S^{2,1}$
$Q_S^{2,0}$
Q_C^{1}
Q_C^{0}
$S_{-,1}^{1,1}$ $S_0^{1,1}$ $S_{+,1}^{1,1}$
$S_{-,1,0}^{1,0}$ $S_{-,0,2}^{1,0}$ $S_{-,0,1}^{1,0}$ $S_{0,0}^{1,0}$ $S_{+,0,1}^{1,0}$ $S_{+,0,2}^{1,0}$ $S_{+,1,0}^{1,0}$
$S_{-,1}^{2,1}$ $S_0^{2,1}$ $S_{+,1}^{2,1}$
$S_{-,1,2}^{2,0}$ $S_{-,1,1}^{2,0}$ $S_{-,1,0}^{2,0}$ $S_{0,0}^{2,0}$ $S_{+,1,0}^{2,0}$ $S_{+,1,1}^{2,0}$ $S_{+,1,2}^{2,0}$
$C_{-,2}^{1}$ $C_{-,1}^{1}$ C_0^{1} $C_{+,1}^{1}$ $C_{+,2}^{1}$
$C_{-,2,1}^{0}$ ••• $C_{-,0,1}^{0}$ $C_{0,0}^{0}$ $C_{+,0,1}^{0}$ ••• $C_{+,2,1}^{0}$
Δ Δ Δ Δ Δ 2Δ Δ Δ Δ Δ Δ

Fig. 1

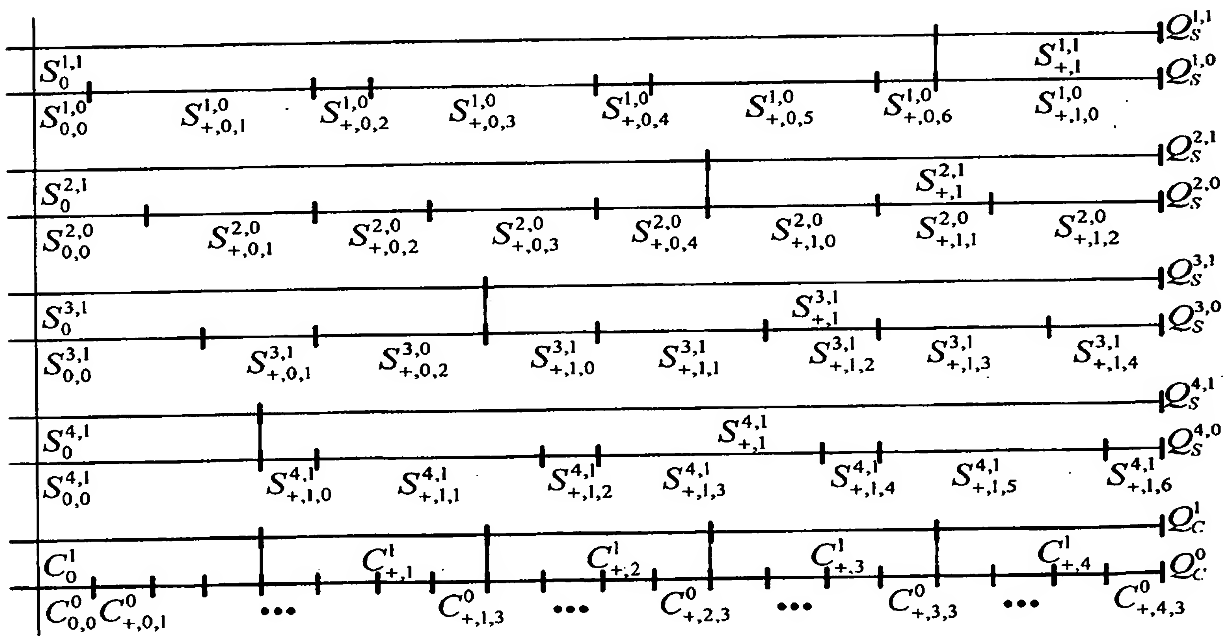
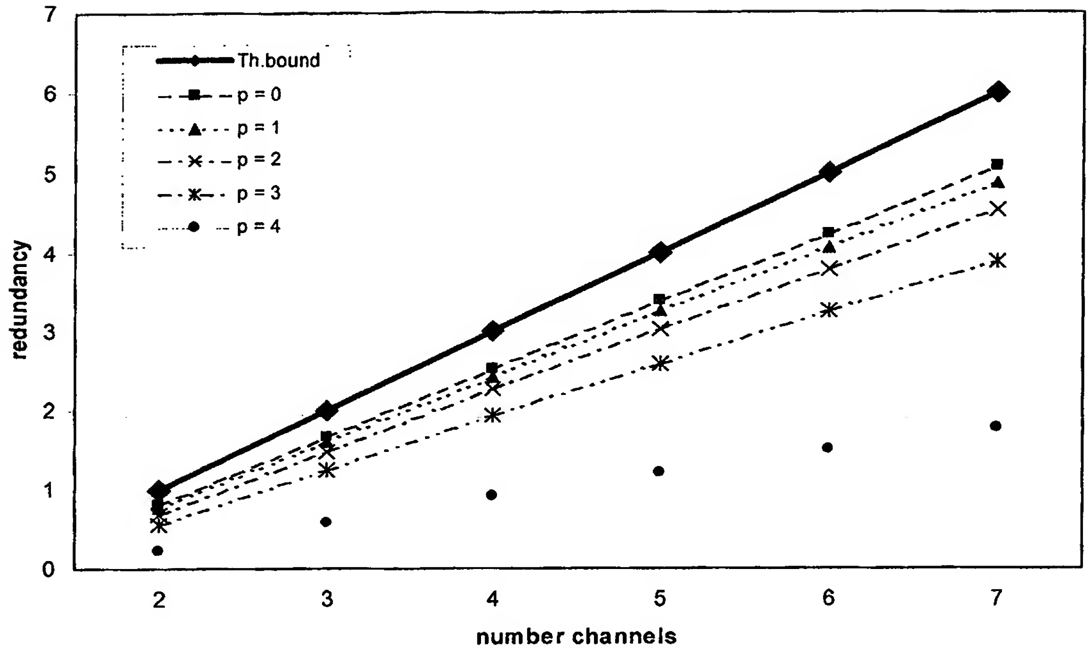
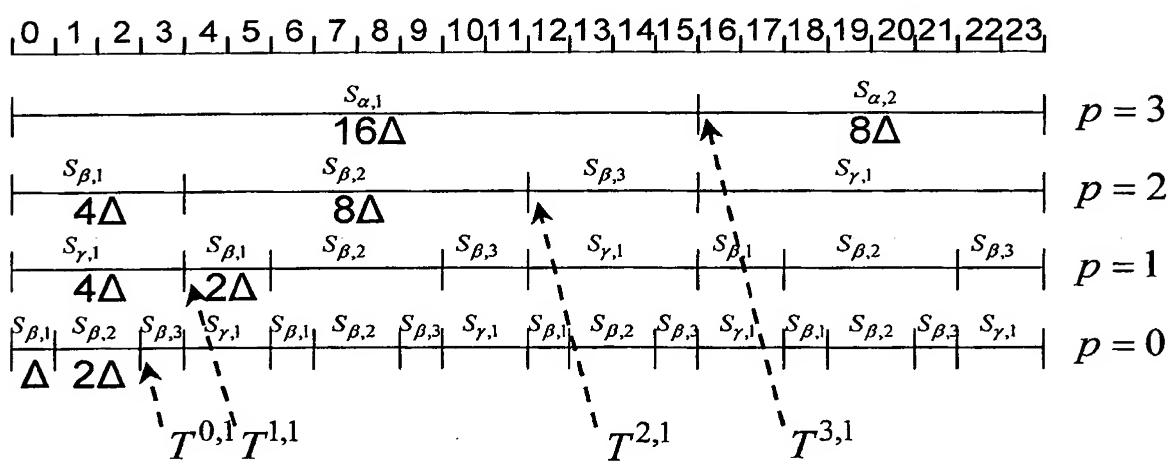

$Q_S^{1,1}$
$Q_S^{1,0}$
$Q_S^{2,1}$
$Q_S^{2,0}$
$Q_S^{3,1}$
$Q_S^{3,0}$
$Q_S^{4,1}$
$Q_S^{4,0}$
Q_C^{1}
Q_C^{0}
$S_0^{1,1}$ $S_{+,1}^{1,1}$
$S_{0,0}^{1,0}$ $S_{+,0,1}^{1,0}$ $S_{+,0,2}^{1,0}$ $S_{+,0,3}^{1,0}$ $S_{+,0,4}^{1,0}$ $S_{+,0,5}^{1,0}$ $S_{+,0,6}^{1,0}$ $S_{+,1,0}^{1,0}$
$S_0^{2,1}$ $S_{+,1}^{2,1}$
$S_{0,0}^{2,0}$ $S_{+,0,1}^{2,0}$ $S_{+,0,2}^{2,0}$ $S_{+,0,3}^{2,0}$ $S_{+,0,4}^{2,0}$ $S_{+,1,0}^{2,0}$ $S_{+,1,1}^{2,0}$ $S_{+,1,2}^{2,0}$
$S_0^{3,1}$ $S_{+,1}^{3,1}$
$S_{0,0}^{3,1}$ $S_{+,0,1}^{3,1}$ $S_{+,0,2}^{3,0}$ $S_{+,1,0}^{3,1}$ $S_{+,1,1}^{3,1}$ $S_{+,1,2}^{3,1}$ $S_{+,1,3}^{3,1}$ $S_{+,1,4}^{3,1}$
$S_0^{4,1}$ $S_{+,1}^{4,1}$
$S_{0,0}^{4,1}$ $S_{+,1,0}^{4,1}$ $S_{+,1,1}^{4,1}$ $S_{+,1,2}^{4,1}$ $S_{+,1,3}^{4,1}$ $S_{+,1,4}^{4,1}$ $S_{+,1,5}^{4,1}$ $S_{+,1,6}^{4,1}$
C_0^{1} $C_{+,1}^{1}$ $C_{+,2}^{1}$ $C_{+,3}^{1}$ $C_{+,4}^{1}$
$C_{0,0}^{0}$ $C_{+,0,1}^{0}$ ••• $C_{+,1,3}^{0}$ ••• $C_{+,2,3}^{0}$ ••• $C_{+,3,3}^{0}$ ••• $C_{+,4,3}^{0}$

Fig. 2



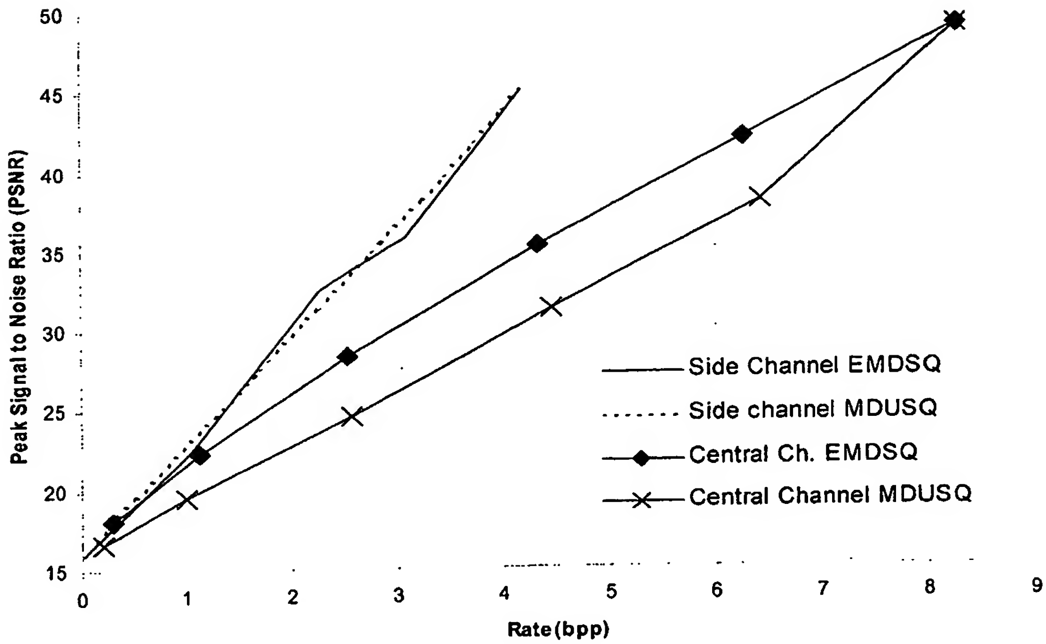
Th.bound
p = 0
p = 1
p = 2
p = 3
p = 4
redundancy
number channels

Fig. 3



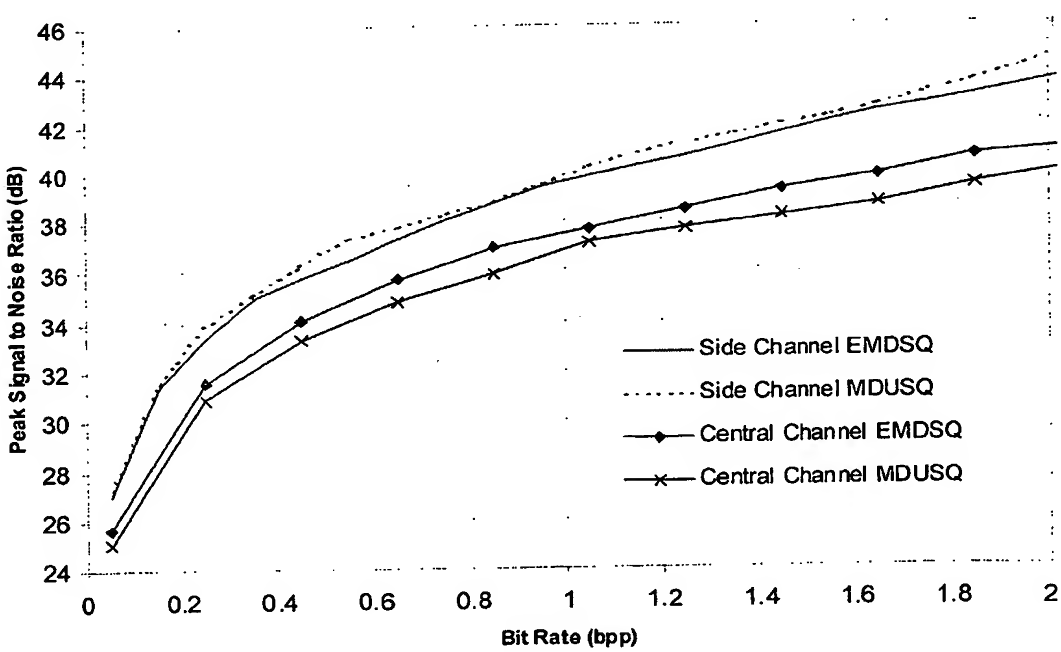
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
$S_{\alpha,1}$ 16Δ
$S_{\alpha,2}$ 8Δ
$p=3$
$S_{\beta,1}$ 4Δ
$S_{\beta,2}$ 8Δ
$S_{\beta,3}$
$S_{\gamma,1}$
$p=2$
$S_{\gamma,1}$ 4Δ
$S_{\beta,1}$ 2Δ
$S_{\beta,2}$
$S_{\beta,3}$
$S_{\gamma,1}$
$S_{\beta,1}$
$S_{\beta,2}$
$S_{\beta,3}$
$p=1$
$S_{\beta,1}$ Δ
$S_{\beta,2}$ 2Δ
$S_{\beta,3}$
$S_{\gamma,1}$
$p=0$
$T^{0,1}$
$T^{1,1}$
$T^{2,1}$
$T^{3,1}$

Fig. 4



50
45
40
35
30
25
20
15
Peak Signal to Noise Ratio (PSNR)
0
1
2
3
4
5
6
7
8
9
Rate (bpp)
Side Channel EMDSQ
Side channel MDUSQ
Central Ch. EMDSQ
Central Channel MDUSQ

Fig. 5

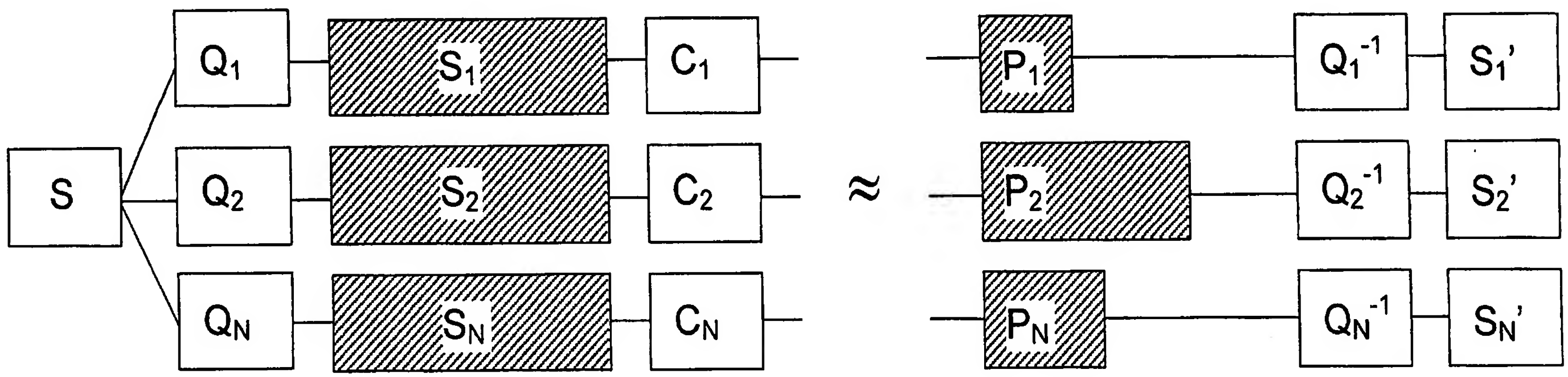


46
44
42
40
38
36
34
32
30
28
26
24
Peak Signal to Noise Ratio (dB)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Bit Rate (bpp)
Side Channel EMDSQ
Side Channel MDUSQ
Central Channel EMDSQ
Central Channel MDUSQ

Fig. 6

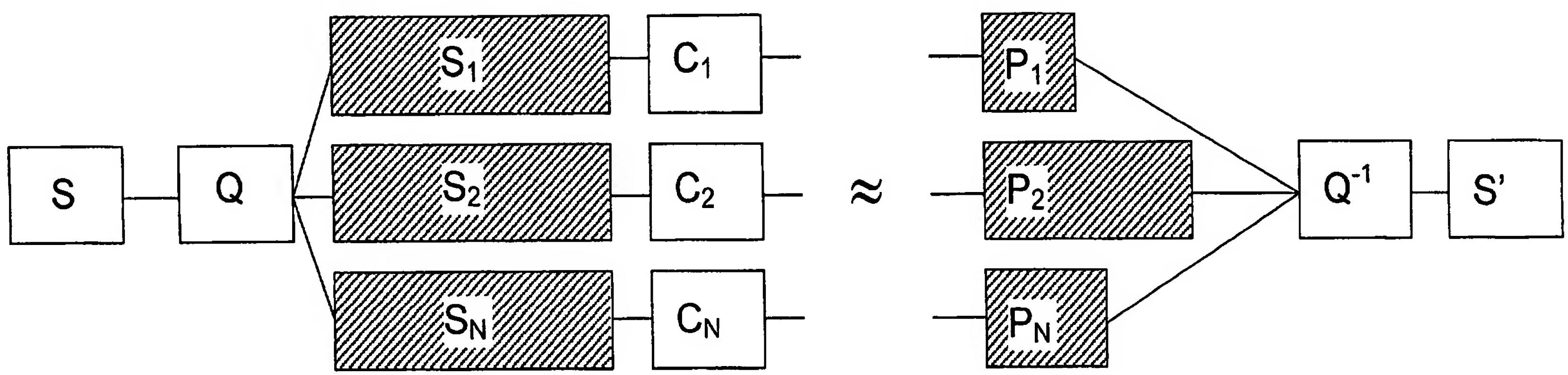
Image	Quant.	0.125	0.25	0.5	1	2	4
barb.raw	EMDSQ	23.90	25.72	28.52	32.56	37.75	44.52
	MDUSQ	23.63	24.87	28.20	32.16	37.15	42.85
bird.raw	EMDSQ	30.98	34.31	37.94	41.46	44.82	50.04
	MDUSQ	30.15	33.40	37.15	40.66	43.78	48.88
boat.raw	EMDSQ	26.09	28.48	31.23	34.84	39.72	44.92
	MDUSQ	25.62	27.73	30.46	33.85	38.30	43.80
camera.raw	EMDSQ	23.32	25.26	28.08	31.78	37.06	44.43
	MDUSQ	22.59	24.80	27.50	30.87	36.21	43.08
mandrill.raw	EMDSQ	20.99	21.90	23.51	25.97	29.59	35.50
	MDUSQ	20.59	21.57	22.91	25.25	28.94	34.51
average mean diff.		0.54	0.66	0.61	0.76	0.91	1.25

Fig. 7



S
Q1
Q2
QN
S1
S2
SN
C1
C2
CN
≈
P1
P2
PN
Q1-1
Q2-1
QN-1
S1'
S2'
SN'

Fig. 8



S
Q
S1
S2
SN
C1
C2
CN
≈
P1
P2
PN
Q-1
S'

Fig. 9

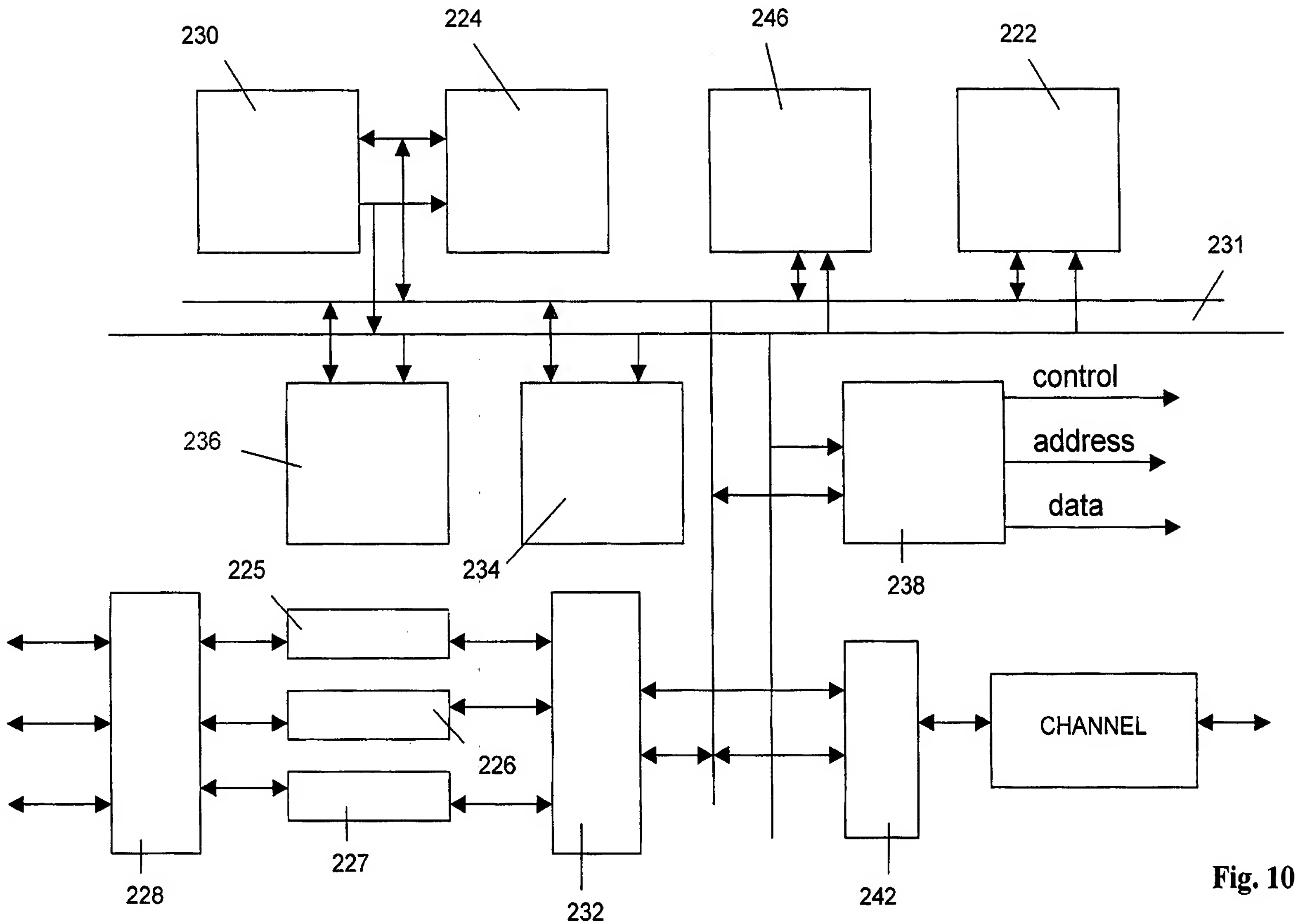
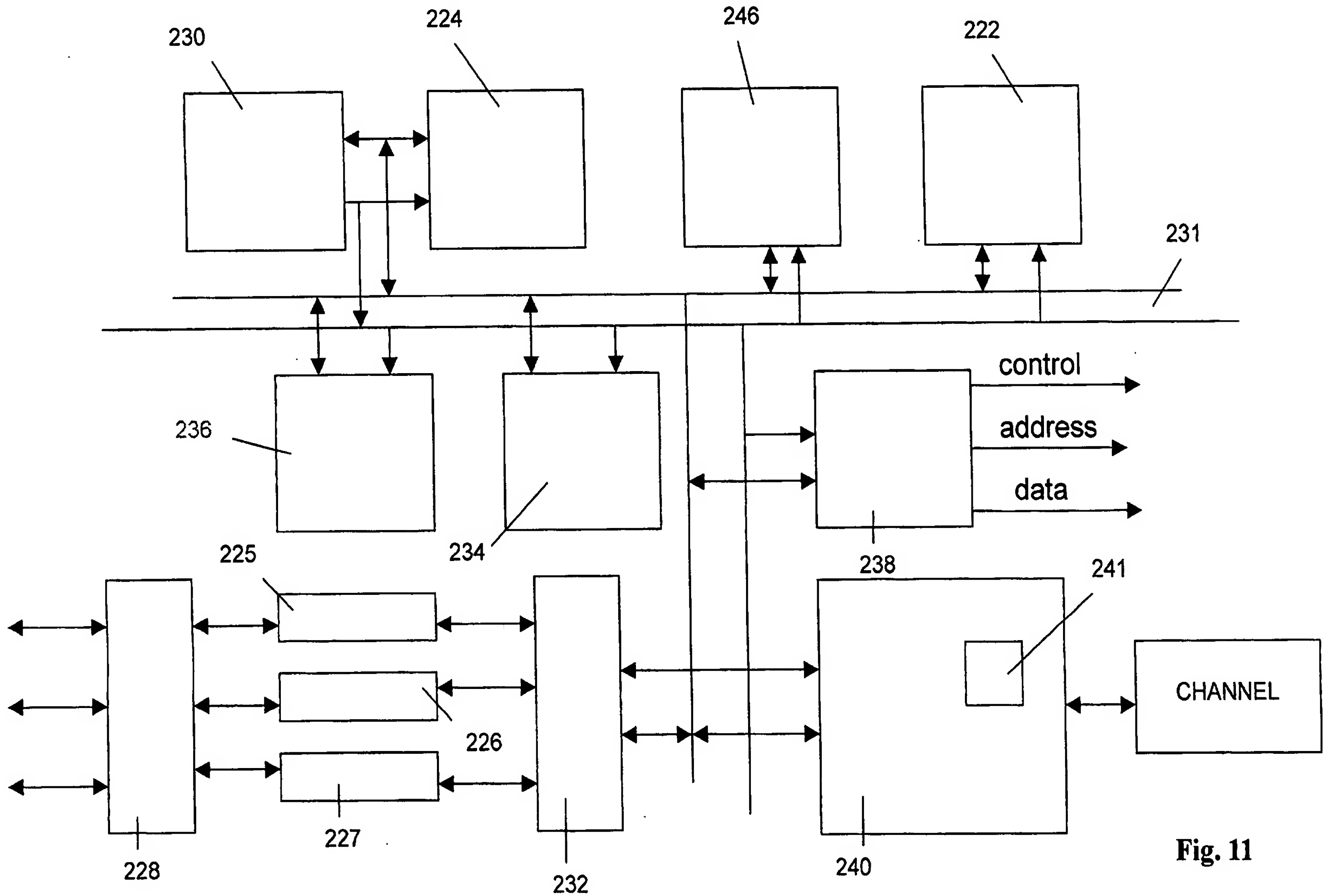

230
224
246
222
231
236
234
control
address
data
238
225
226
227
228
232
242
CHANNEL

Fig. 10



230
224
246
222
231
236
234
control
address
data
238
225
226
227
228
232
240
241
CHANNEL

Fig. 11